Environmental policy and technology diffusion under imperfect competition

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Chapter 8

Marketable permits versus credits

8.1 Introduction

Both subsidies and taxation try to diminish pollution by affecting firm behavior in an indirect way by putting a price tag on emissions either in the form of a reward for emission reduction or a penalty on emissions respectively. The firm encounters a change in the level of profits, but to a different sign, i.e., subsidies have a direct positive effect on profits whereas the emission tax has a direct negative effect. How the instruments affect total pollution depends on the amount of output that is produced by the firms. The control authority does not impose any limits on the total amount of emissions, i.e., under taxation and subsidies firm-level emissions and total industry emissions still have some degrees of freedom to fluctuate.

This is different with a system of tradable emission permits (or cap-and-trade schemes) and tradable emission credits and the incentive mechanism is to some extent the counterpart of the taxation and subsidy instrument. Under permits the level of total industry emissions is set to a concrete fixed level (emission ceiling) and the permit price adjusts in such a way that actual emissions remain below this target. A system of tradable credits is built upon the mechanism that applies to permits, but now the emission target is tied to output by means of an emission standard, which defines the quantity of a pollutant a firm is allowed to emit per unit of output. Firms that generate fewer emissions than they are entitled to given their output, receive credits which they can sell to firms that want to emit more than the emission standard multiplied with their output allows to. Here the credit price adjusts actual emissions to the emission target that varies with total industry output. A discussion and comparison of tradable permits and tradable credits can be found in chapter 2 of Nentjes *et al.* (2002) and Woerdman (2002). This chapter discusses these two policy variants with regard to the question how they affect the diffusion of clean technology.

The chapter is organized as follows. In section 8.2 we give the optimization problems of the firms under a permit and credit regime and derive the optimal Cournot-Nash quantities and the analytical expressions of the permit and credit price. In section 8.3 we derive the expressions for the evolutionary equilibria and conduct a comparative statics exercise. Section 8.4 contains a numerical example. In section 8.5 we examine the buyer/seller role of firms in the market for permits and credits and specifically determine which firms are sellers and buyers given the state of diffusion. A sensitivity analysis is conducted in section 8.6. The chapter ends with conclusions in section 8.7.

8.2 The optimization problems

As stated before, a government is unable to control the pollution level directly under a taxation and subsidy policy. It simply has to wait and see whether the tax rate or subsidy rate that has been set, is sufficiently high to bring emissions down to the desired level the government is aiming at. In case of tradable permits, the government sets an overall pollution target and issues a number of emission permits equal to this emission cap. The permit price should adjust in such a way that demand for permits and their use to cover emissions does not surpass the available supply of permits handed out by the government.

Permits can be issued freely (grandfathering) or by auction. For the equilibrium permit price it does not make any difference which method of allocation is chosen (e.g. Spulber, 1989; Dijkstra, 1999). This also applies to the innovation incentive, i.e., the incentive to adopt new technologies is the same under both grandfathered or auctioned permits (e.g. Requate and Unold, 2003; Keohane, 1999; Montero, 2002), as we have seen in chapter 4. So, for the aim of this chapter it is not essential to include an additional auction market and we shall therefore consider a situation where the total amount of permits is distributed freely among the number of firms that operate in the industry. Additionally, it is assumed that firms are price takers in both the permit and credit market. We thus avoid issues of strategic interaction and market power on tradable permit markets[1]. We start by examining a tradable permit system (subsection 8.2.1) and then make the step to the discussion of a market for tradable credits (subsection 8.2.2).

8.2.1 Tradable permits

Assume that before firms start producing, the control authority sets an overall industry emission target L. Following a grandfathering approach, given the number of N competitors, each firm is then initially endowed with a number of permits equal to L/N. Each permit allows a firm to emit one unit of the pollutant and the permits may be traded among the firms. The maximization problem for a technology j-type firm under the permit policy $k = per$ can now be posed as:

$$\max_{x_j^{per}} \pi_j^{per} = p_j^{per} x_j^{per} - c_j^{per} - \sigma e_j^{per}, \tag{8.1}$$

subject to the usual non-negativity constraints $x_j^{per} \geq 0$. As we see from (8.1), profits equal revenues minus costs *and* the amount of permits the firm holds to cover emissions at price σ. It is assumed that firms are price takers on the market for tradable permits. Therefore, the permit price σ is given when the firm decides how much to produce.

Firm-level emissions have to be covered by the amount of permits. That this should hold in case of auctioning is clear enough. Every amount of emissions a firm wants to emit requires expenditures to buy the permits that allow the firm to pollute up to this specific level. However, in case of grandfathering all permits, including those that have been received for free, are costs as well. The firm sacrifices the opportunity to sell the permits by using its free permits to cover emissions. These sacrificed revenues are the opportunity costs of permits used to cover emissions. Compared to a firm that uses all its free received permits, a firm that is a seller of permits has an advantage in terms of lower opportunity costs.

Substitution of the price function (6.1), the production costs (6.7) and the emission function (6.9) into (8.1) and rewriting gives the explicit form of the

[1] A guide to the relevant literature is given in Koster (2001) where she discusses, among others, the classical reference of Hahn (1984), Westskog (1996) and Hagem and Westskog (1998).

maximization problem of the dirty and clean firm under permits:

$$\max_{x_d^{per}} \pi_d^{per} = (\theta_d - \sigma\zeta_d - \beta(\widehat{X}_d^{per} + x_d^{per}) - \gamma X_c^{per})x_d^{per} - \mu_d, \tag{8.2}$$
$$\max_{x_c^{per}} \pi_c^{per} = (\theta_c - \sigma\zeta_c - \beta(\widehat{X}_c^{per} + x_c^{per}) - \gamma X_d^{per})x_c^{per} - \mu_c,$$

with the net absolute advantage θ_j ($j = d, c$) as defined in (6.8) and $\widehat{X}_j^{per}$ ($j = d, c$) given in (6.12). Recall that the firm is assumed to be a price-taker in the market for tradable permits, implying that the optimal production levels are determined by the simultaneous solution to the first-order conditions $d\pi_j^{per}/dx_j^{per} = 0$ ($j = d, c$) for a *given* permit price σ. The first-order conditions regarding (8.2) are:

$$\frac{\partial \pi_d^{per}}{\partial x_d^{per}} = \theta_d - \sigma\zeta_d - \beta(\widehat{X}_d^{per} + x_d^{per}) - \gamma X_c^{per} - \beta x_d^{per} = 0, \tag{8.3}$$
$$\frac{\partial \pi_c^{per}}{\partial x_c^{per}} = \theta_c - \sigma\zeta_c - \beta(\widehat{X}_c^{per} + x_c^{per}) - \gamma X_d^{per} - \beta x_c^{per} = 0,$$

where $X_d^{per} = (1-s)Nx_d^{per}$ and $X_c^{per} = sNx_c^{per}$. The simultaneous solution to (8.3) defines the firm-level Cournot-Nash quantities as a function of s and permit price σ:

$$x_d^{per} = \frac{\beta(sN+1)(\theta_d - \sigma\zeta_d) - \gamma sN(\theta_c - \sigma\zeta_c)}{\Theta}, \tag{8.4}$$
$$x_c^{per} = \frac{\gamma(s-1)N(\theta_d - \sigma\zeta_d) - \beta((s-1)N-1)(\theta_c - \sigma\zeta_c)}{\Theta},$$

with Θ as in (6.16).

The conditions for profit maximization include the demand and cost functions and assume that demand for outputs equals produced output. Therefore, (8.3), or alternatively (8.4), has to be interpreted as the market clearing condition for the oligopolistic output market. The market clearing condition for the tradable permit market reads:

$$\zeta_d X_d^{per} + \zeta_c X_c^{per} = L. \tag{8.5}$$

The left-hand-side of (8.5) represents the market demand for permits, which is determined by the level and composition of output. The right-hand-side of (8.5) is the supply of permits, which has been made available by the government. The permit supply is simply equal to the imposed emission ceiling L. In short, equation (8.5) states the condition for equilibrium on the permit market: demand for permits equals permit supply which is fixed.

From the modelling structure it is clear that the permit price is not determined separately on the permit market, but in the simultaneous equilibrium on the permit and output market. If emissions tend to exceed the available quantity of permits, excess demand for permits is prevented by an increase in the permit price σ, which basically has the same effect on production as a higher level of an emission tax[2]. The marginal cost of clean and dirty products will rise, but for the dirty variant more than the the clean one, hence inducing profit maximizing oligopolistic firms to produce less and charge higher prices. Both the supply of the clean and dirty firm-level quantities decrease, i.e., $\partial x_j^{per}/\partial\sigma < 0$ $(j = d, c)$. Lower output brings down emissions, thus restoring the equilibrium between permit demand and supply. So, the permit price has no direct effect on emissions, but influences them through its effect on the output market.

The final form of the permit price can be found by substituting (8.4) into (8.5). Then solving for σ yields the permit price as a function of diffusion s. After some rearranging the permit price equals:

$$\sigma = \frac{a_0 + a_1 s + a_2 s^2}{a_3 + a_4 s + a_5 s^2}, \tag{8.6}$$

where the constants read:

$$\begin{aligned}
a_0 &= \beta\left[L(N+1)\beta - \zeta_d N\theta_d\right], \\
a_1 &= N[L(\beta^2-\gamma^2)N + (\gamma N\theta_c - \beta(N-1)\theta_d)\zeta_d - (\beta(N+1)\theta_c - \gamma N\theta_d)\zeta_c], \\
a_2 &= N^2[L(\gamma^2-\beta^2) - (\gamma\theta_c - \beta\theta_d)\zeta_d + (\beta\theta_c - \gamma\theta_d)\zeta_c], \\
a_3 &= -\beta N\zeta_d^2, \\
a_4 &= -N[\beta((N-1)\zeta_d^2 + (N+1)\zeta_c^2) - 2\gamma N\zeta_d\zeta_c], \\
a_5 &= N^2[\beta(\zeta_d^2+\zeta_c^2) - 2\gamma\zeta_d\zeta_c].
\end{aligned}$$

From (8.6) we see that the permit price is nonlinear in the diffusion state s. As diffusion advances, the permit price changes accordingly:

$$\frac{d\sigma}{ds} \lesseqgtr 0 \Longleftrightarrow \frac{a_1 + 2a_2 s}{a_0 + a_1 s + a_2 s^2} \lesseqgtr \frac{a_4 + 2a_5 s}{a_3 + a_4 s + a_5 s^2}. \tag{8.7}$$

[2] Note that the Cournot-Nash quantities under taxation and permits are for a *given* tax rate τ and *given* permit price σ respectively. The uniform emission tax is, however, exogenous in our model while the permit price is endogenous. Of course, we assume that when supplying the optimal quantities the permit price is given for the firm, but contrary to emission taxation and the subsidy policy, it is endogenous with respect to the technological distribution within the industry, i.e., the proportions of dirty and clean type firms. See also Keohane (1999) and Requate and Unold (2003) for a discussion on this.

When σ increases both the price of the dirty and clean good increase, hence discouraging overall demand[3]. An increasing permit price implies that the price of the dirty product becomes relatively more expensive compared to the price of the clean product, i.e., p_c decreases relative to p_d. Hence the production of the dirty good will decrease relative to the output level of the innovative firm. The substitution of clean for dirty output tends to decrease emissions. More precisely, in case the increase of total output threatens to push emissions upwards (and above the cap L), the rise in the permit price and the change in composition of output involves that total emissions stay below the emission ceiling L. Next to that, there is the effect of a higher permit price on total output which also contributes to lowering emissions, as explained before.

Equation (8.7) shows when $\partial\sigma/\partial s \lesseqgtr 0$. Intuitively, it would seem reasonable at first sight to presume a strictly decreasing permit price in the degree of technology diffusion. When more firms switch to the manufacturing of clean products (s increases), one could expect the 'demand' for pollution to become lower, which in turn would induce the permit price to go down. In the numerical example that will be presented below, we will show that this is not always the case when the permit price is contingent on the behavior of firms in an imperfect output market. But first we will discuss a system of tradable emission credits.

8.2.2 Tradable credits

Whereas in a system of tradable emission permits the control authority sets a limit on the total supply of emissions, in case of tradable emission credits the authority imposes an emission standard, which defines the legal maximum amount of pollution per unit of output a firm is allowed to emit. Emission standards with credit trade means that when a firm wants to emit more than the standard multiplied with output allows to, it can buy emission credits from firms that are capable to emit less than emission standard and output would allow. The result is that, in average, the industry as a whole complies with the emission standard, but the individual firm has the flexibility to divert from the standard[4]. In a scheme of emission standards with credit trade, total emissions are not bound by a ceiling. If both total output of clean and dirty goods increase by, let's say 10 percent, the total allowed emissions also increase by 10 percent. Here lies the main difference between permits and credits. Instead of

[3]Due to $\partial p_j^k/\partial\sigma > 0$, demand decreases and $\partial x_j^k/\partial\sigma < 0$.

[4]A scheme of NO_x emission standards with credit trade for energy intensive industries is planned to be introduced in the Netherlands in 2004. A similar scheme has been proposed for CO_2 emissions (Vogtländer, 2001).

imposing an overall emission target L as under permits, the control authority now introduces an emission standard δ. To be feasible, the emission standard $\delta \in (\zeta_c, \zeta_d)$.

Under the tradable permit regime profits were defined as $\pi_j^{per} = p_j^{per} x_j^{per} - c_j^{per} - \sigma e_j^{per}$. The term $p_j^{per} x_j^{per} - c_j^{per}$ simply reflects revenues minus production costs. In a scheme with grandfathered permits, the term σe_j^{per} represents the revenue loss of not selling permits but instead using them as a production input plus, possibly, expenditures for buying additional permits when the firm is a permit buyer. We see that the permit cost depends on the total amount of firm-level emissions e_j^{per}. Under credits it is essentially this term that should be adjusted for the emission standard δ. The firm has only credit costs for its excess emissions, either positive or negative.

Under a tradable credit policy the firm adopting technology $j = d, c$ faces a maximization problem according to:

$$\max_{x_j^{cre}} \pi_j^{cre} = p_j^{cre} x_j^{cre} - c_j^{cre} - \phi(e_j^{cre} - \delta x_j^{cre}), \tag{8.8}$$

where ϕ denotes the credit price. Substitution of $e_j^{cre} = \zeta_j x_j^{cre}$ in (8.8) and rearranging yields an expression for the profit-maximizing firm like:

$$\max_{x_j^{cre}} \pi_j^{cre} = p_j^{cre} x_j^{cre} - c_j^{cre} - \phi(\zeta_j - \delta) x_j^{cre}, \tag{8.9}$$

subject to:

$$\sum_{j=d,c} \zeta_j X_j^{cre} = \delta \sum_{j=d,c} X_j^{cre}. \tag{8.10}$$

Comparing (8.9) with (8.1) shows that the difference is the emission standard δ only; however, condition (8.10), which ensures equilibrium on the credit market, is now also subject to variability. That is, the credit supply [the right-hand-side of equation (8.10)] is dependent on the level and composition of aggregate output X_j^{cre} [as defined in (6.4)] instead of being fixed as is the case under permits[5].

Now substitute the price functions (6.1), the cost functions (6.7) and emission functions (6.9) into (8.9). After some rearranging the profit functions to be maximized given the adoption of technology $j = d, c$ can be expressed as:

$$\max_{x_d^{cre}} \pi_d^{cre} = (\theta_d - \phi(\zeta_d - \delta) - \beta(\widehat{X}_d^{cre} + x_d^{cre}) - \gamma X_c^{cre}) x_d^{cre} - \mu_d, \tag{8.11}$$
$$\max_{x_c^{cre}} \pi_c^{cre} = (\theta_c - \phi(\zeta_c - \delta) - \beta(\widehat{X}_c^{cre} + x_c^{cre}) - \gamma X_d^{cre}) x_c^{cre} - \mu_c,$$

[5] Of course, we could rewrite (8.10) as $\delta = \frac{\sum_{j=d,c} \zeta_j X_j}{\sum_{j=d,c} X_j}$, where δ is a fixed number.

subject to the market clearing constraint:

$$\zeta_d X_d^{cre} + \zeta_c X_c^{cre} = \delta(X_d^{cre} + X_c^{cre}). \tag{8.12}$$

The emission standard δ is given and $\zeta_c < \delta < \zeta_d$. In order to avoid an arbitrary comparison between permits and credits, we calibrate the value of δ in first instance based upon the final diffusion equilibrium outcome under permits, i.e.,

$$\delta = \frac{L}{\widetilde{X}_d^{per} + \widetilde{X}_c^{per}}, \tag{8.13}$$

where $\widetilde{X}_j^{per}$ $(j = d, c)$ is the value of industry output in the evolutionary equilibrium $\tilde{s}^{per}$.

Recall there is simultaneous coordination. The output market clears at prices p_j $(j = d, c)$ and the credit market clears at credit prices ϕ. Alike the firms in the permit market, the firms in the market for credits are also price-takers. The first-order conditions of (8.11) for a *given* credit price ϕ and *given* emission standard δ read:

$$\begin{aligned}
\frac{\partial \pi_d^{cre}}{\partial x_d^{cre}} &= \theta_d - \sigma(\zeta_d - \phi) - \beta(\widehat{X}_d^{cre} + x_d^{cre}) - \gamma X_c^{cre} - \beta x_d^{cre} = 0, \quad (8.14)\\
\frac{\partial \pi_c^{cre}}{\partial x_c^{cre}} &= \theta_c - \sigma(\zeta_c - \phi) - \beta(\widehat{X}_c^{cre} + x_c^{cre}) - \gamma X_d^{cre} - \beta x_c^{cre} = 0,
\end{aligned}$$

and generate the following Cournot-Nash output quantities:

$$\begin{aligned}
x_d^{cre} &= \frac{\beta(sN+1)(\theta_d - \phi(\zeta_d - \delta)) - \gamma sN(\theta_c - \phi(\zeta_c - \delta))}{\Theta}, \quad (8.15)\\
x_c^{cre} &= \frac{\gamma(s-1)N(\theta_d - \phi(\zeta_d - \delta)) - \beta((s-1)N - 1)(\theta_c - \phi(\zeta_c - \delta))}{\Theta},
\end{aligned}$$

again with Θ given in (6.16).

The credit price can be determined by the same routine as the permit price under the permit regime, i.e., by substituting (8.15) into (8.12) and solving for ϕ yields the credit price:

$$\phi = \frac{b_0 + b_1 s + b_2 s^2}{b_3 + b_4 s + b_5 s^2}, \tag{8.16}$$

where the constants read:

$$\begin{aligned}
b_0 &= \beta(\delta-\zeta_d)\theta_d, \\
b_1 &= [\beta(N+1)(\delta-\zeta_c)-\gamma N(\delta-\zeta_d)]\,\theta_c+[\beta(N-1)(\delta-\zeta_d)-\gamma N(\delta-\zeta_c)]\,\theta_d, \\
b_2 &= N[((\gamma-\beta)\delta+\beta\zeta_c-\gamma\zeta_d)\theta_c+((\gamma-\beta)\delta+\gamma\zeta_c-\beta\zeta_d)\theta_c] \\
b_3 &= -\beta(\delta-\zeta_d)^2, \\
b_4 &= 2\delta^2N(\gamma-\beta)-\beta\zeta_c^2(N+1)+2\delta\zeta_d(\beta(N-1)-\gamma N)+\beta\zeta_d^2(1-N)+ \\
&\qquad 2\delta\zeta_c(\beta(N+1)-\gamma N)+\gamma\zeta_d\zeta_c, \\
b_5 &= 2\delta(\beta-\gamma)(\delta-\zeta_c)+\zeta_c(\beta\zeta_c-2\gamma\zeta_d)+\zeta_d(2\delta(\gamma-\beta)+\beta\zeta_d).
\end{aligned}$$

In order to get some feeling about the working of the two policy options, we will provide a numerical example in section 8.4 to illustrate how the optimal firm-level output quantities, aggregate emissions and the permit and credit price behave. But before doing so, we shall first derive analytically the evolutionary equilibria under the permit and credit regime, followed by a comparative static analysis.

8.3 Policy equilibria and comparative statics

As was done under the policy regimes laissez faire, taxation and subsidies, the interior stable states of diffusion $\tilde{s}$ under permits and credits can be obtained by solving $\Delta\pi = 0$ for s. After simplifying and rearranging, the evolutionary equilibria under permits and credits are reduced to the ones given in table 8.1.

Table 8.1: *Evolutionary equilibria under permits and credits.*

Policy	$\tilde{s}$
permits	$\frac{L[\beta(\zeta_d-\zeta_c(N+1))+\gamma\zeta_d N]+\zeta_d N(\theta_d\zeta_c-\theta_c\zeta_d)}{N[L(\gamma-\beta)(\zeta_d+\zeta_c)+(\zeta_d-\zeta_c)(\theta_d\zeta_c-\theta_c\zeta_d)]}$
credits	$\frac{\zeta_d-\delta}{\zeta_d-\zeta_c}$

One of the relevant questions is how a more stringent policy by lowering the emission ceiling L or a more strict emission standard δ, will affect the final diffusion equilibrium outcome under permits and credits respectively. Let's start with the former. It could be expected that lowering the overall target level of pollution would induce more firms to adopt the clean technology in the long run. So, the hypothesis to be tested states that the control authority should tighten its environmental policy by lowering the emission ceiling L in order to achieve a higher penetration of clean technology. The comparative static result reads:

$$\frac{\partial \tilde{s}^{per}}{\partial L} = \frac{[\beta(N+1)(\zeta_c^2+\zeta_d^2) - 2(\beta+\gamma N)\zeta_c\zeta_d](\zeta_c\theta_d - \zeta_d\theta_c)}{N[\zeta_d(L(\beta-\gamma)+\zeta_d\theta_c) + \zeta_c(L(\beta-\gamma) - \zeta_d(\theta_c+\theta_d)) + \zeta_c^2\theta_d]^2} \lesseqgtr 0. \tag{8.17}$$

This leads us to the following proposition:

Proposition 2 *A more stringent environmental policy under a tradable permit scheme, in terms of lowering the emission ceiling L, enhances the diffusion of clean technology if and only if $\zeta_c/\zeta_d < \theta_c/\theta_d$.*

Proof. In appendix 8A. ■

However, based on proposition 2 we can pose the following more general argument:

Corollary 3 *Lowering the emission ceiling L will stimulate the diffusion of clean technology in the long-run if the clean firm faces a net absolute advantage which is at least as high as the net absolute advantage of the dirty firm.*

Proof. The proof is straightforward. Based on proposition 2 $\partial \tilde{s}^{per}/\partial L < 0 \Longleftrightarrow \zeta_c/\zeta_d < \theta_c/\theta_d$. By definition, $\zeta_c < \zeta_d \Longrightarrow \zeta_c/\zeta_d < 1$. If $\theta_c/\theta_d \geq 1 > \zeta_c/\zeta_d \Longrightarrow \partial \tilde{s}^{per}/\partial L < 0$. ■

In our setup, the clean firm faces a net absolute advantage over the dirty firm ($\theta_c > \theta_d$), making the term $\zeta_c\theta_d - \zeta_d\theta_c < 0$. Therefore in our specific case $\partial \tilde{s}^{per}/\partial L < 0$; a more stringent policy represented by a lower emission ceiling thus enhances the penetration of clean technology. Note that this inequality applies to products being imperfect substitutes (and the clean and dirty technology being different in terms of pollution per unit of production). We can also specify the marginal effect of a change in the emission ceiling L when product substitutability increases, i.e., the difference between the direct price effect β and cross price effect γ gets smaller. This limit case results in $\lim_{\gamma\to\beta} \partial\tilde{s}^{per}/\partial L = \frac{\beta(N+1)}{N(\zeta_c\theta_d-\zeta_d\theta_c)} \lesseqgtr 0$ if and only if $\zeta_c\theta_d - \zeta_d\theta_c \lesseqgtr 0$. With $\zeta_d > \zeta_c$ and $\theta_c > \theta_d$, the marginal effect is negative and supports our hypothesis that a more stringent emission ceiling leads to more firms adopting the clean technology. However, in the limit as $\gamma \to \beta$, the effect is positive if $\theta_c < \theta_d$.

Maybe a somewhat unrealistic scenario, but what happens to the final diffusion equilibrium when the emission ceiling L approaches zero? We then find:

$$\lim_{L\to 0} \tilde{s}^{per} = \frac{\zeta_d}{\zeta_d - \zeta_c} > 1. \tag{8.18}$$

By definition, s is truncated above at 1, implying that the industry becomes completely specialized in the clean good when the emission ceiling approaches zero. Because (8.18) is bigger than 1, an industry only comprising firms with a clean production mode can be established for a certain value of $L > 0$. This can easily be calculated by solving $\tilde{s}^{per} = 1$ for L. The solution reads:

$$L = \frac{\zeta_c N(\zeta_c\theta_d - \zeta_d\theta_c)}{(\beta+\gamma N)\zeta_c - \beta(N+1)\zeta_d} > 0 \Longleftrightarrow \frac{\zeta_c}{\zeta_d} < \frac{\theta_c}{\theta_d}. \tag{8.19}$$

Turning to the evolutionary equilibrium under the credit regime, we find that an increase in the emission standard yields a lower equilibrium degree of diffusion $\tilde{s}^{cre}$, i.e., $\partial\tilde{s}^{cre}/\partial\delta = -\frac{1}{\zeta_d-\zeta_c} < 0$. This means that a tighter emission standard, implying that a firm is allowed to emit less per unit of production, imposes more pressure on the environmental performance of a firm and therefore also more pressure on a firm to adopt the clean technology.

Furthermore, since $\zeta_c < \delta < \zeta_d$, a marginal change in the emission/output ratio's ζ_j $(j = d, c)$ implies a higher degree of penetration of the clean technology: $\partial\tilde{s}^{cre}/\partial\zeta_d = \frac{\delta-\zeta_c}{(\zeta_c-\zeta_d)^2} > 0$ and $\partial\tilde{s}^{cre}/\partial\zeta_c = \frac{\zeta_d-\delta}{(\zeta_c-\zeta_d)^2} > 0$. From the expression of $\tilde{s}^{cre}$ in table 8.1 it is easy to find that the industry completely specializes in the clean (dirty) good if $\delta = \zeta_c$ (ζ_d) respectively. Or in limit terms: $\lim_{\delta\to\zeta_c} \tilde{s}^{cre} = 1$ and $\lim_{\delta\to\zeta_d} \tilde{s}^{cre} = 0$.

Now we know the expressions for the evolutionary equilibria and know how they are affected by the instrument variables L and δ, it is time to get an intuitive grasp on how the model behaves in more general terms. Like before, we will do so by means of a numerical example.

8.4 A numerical example

To make an adequate comparison with the previous outlined policy regimes possible, we focus on asymmetric firms and use the numerical values of the previous examples. In addition to this, we have to assign exogenously values to the overall emission ceiling L and the emission standard δ. In order to determine the 'correct' value of δ, we first have to calculate the aggregate values of industry output in the evolutionary equilibrium under permits [see equation (8.13)]. Given the initial market conditions as given in the numerical example of the laissez faire case (section 6.5), the average value of industry emissions on the interval $s \in [0, 1]$ under this regime equals 57.7. Now suppose the control authority aims at reducing total emissions below this level and sets the emission ceiling (quite arbitrarily) at, let's say, $L = 40$. We now have all the relevant parameters for finding the associated equilibrium proportion of clean type firms $\tilde{s}^{per}$. By solving $\Delta\pi^{per} = 0$ we get $\tilde{s}^{per} = 0.876$. Substituting this value into (8.4) and aggregation leads to total dirty output $\widetilde{X}_d^{per} = 11.64$ and total clean output $\widetilde{X}_c^{per} = 82.54$. Subsequently, substitution of $L, \widetilde{X}_d^{per}$ and $\widetilde{X}_c^{per}$ into (8.13) yields an emission standard $\delta = 0.425$, which is a constant in the simulation of a credit scheme.

We shall first have a look at numerical values of various relevant variables in the evolutionary equilibria and next discuss the dynamic behavior of the variables during the diffusion process. Table 8.2 presents the values of relevant variables in the evolutionary equilibrium under three policy regimes: permits, credits and laissez faire. Not surprisingly, since we calibrated the emission standard on the outcome under permits, both policies lead to the same unique evolutionary stable diffusion equilibrium $\tilde{s} = 0.876$, meaning that in the long-run clean firms constitute 87.6% of the industry and dirty firms 12.4%. Table 8.2 shows that, in general, the values for the credit scheme are in the intermediate range between the permit scheme and laissez faire, except the price of emissions $\tilde{\phi}$ and aggregate clean output $\widetilde{X}_c$. Since by calibration average emissions per unit of output are equal under permits and credits, the costs of emissions per unit of output are lower under a credit scheme than under permits, because only *excess* emissions have credit costs and *all* emissions bear permit costs. Consequently, both the clean and dirty product price are lower under credits and are therefore closer to the corresponding prices under laissez faire. Lower output prices go hand in hand with higher outputs in the credit scheme. These higher output levels of both the clean and dirty product variant cause a higher volume of emissions and push up the price of emissions. The credit price ϕ is higher than the permit price σ, but evidently not so high as to annihilate the cost advantage of credits relative to permits. Compared to permits, the simulation suggests that credits are good for consumers, bad for the environment and indifferent with regard to diffusion of clean technology.

Table 8.2: *Evolutionary equilibrium values for relevant variables.*

	Policy		
Variable	Laissez faire	Permits	Credits
$\tilde{s}$	0.645	0.876	0.876
$\widetilde{p}_d$	43.3	90.0	65.1
$\widetilde{p}_c$	35.3	64.6	30.8
$\widetilde{X}_d$	44.3	11.6	14.5
$\widetilde{X}_c$	80.3	82.5	103.1
$\widetilde{X}$	124.6	94.1	117.6
$\widetilde{E}$	58.7	40.0	50.0
$\tilde{\sigma}$	-	87.2	-
$\tilde{\phi}$	-	-	131.4

As a next step, let's have a look how prices and quantities change during the diffusion of clean technology. Figure 8.1 depicts the profit differential $\Delta\pi^k$ ($k = per, cre$). With respect to diffusion, under both the permit and credit regime $d\Delta\pi/ds < 0$ and, as already mentioned above, the profit differential is zero at $\tilde{s}^{per} = \tilde{s}^{cre} = 0.876$.

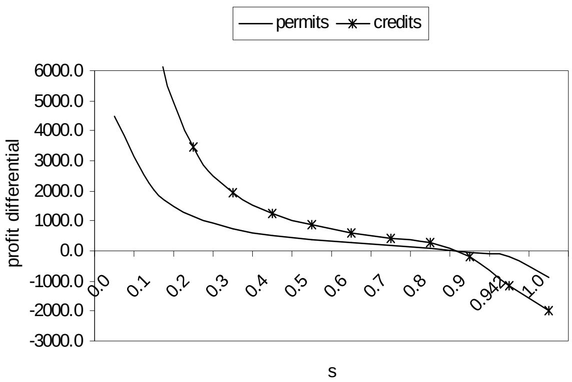

Figure 8.1: *Profit differential under permits and credits.*

Figure 8.1 also indicates that the difference in profits under credits is higher than under permits. To understand this, we have to look at how the permit price σ and credit price ϕ evolve as diffusion of clean technology progresses. Figure 8.2 shows the evolution of σ (8.6) and ϕ (8.16) as a function of diffusion s. Under a credit policy with s being low, there are hardly any credits available in order to meet the demand of the majority of firms facing per unit of output emissions $\zeta_d > \delta$. Excess demand for credits drives up the credit price and yields subsequently high profits for the small group of clean firms selling credits. The supply of credits is zero in $s = 0$ and the credit price is sky high, curtailing output and emissions. On the other hand, if the whole industry only comprises clean firms ($s = 1$), there are only suppliers on the credit market and not a single buyer. The credit price falls to zero and the actual credit regime is then identical to laissez faire. In fact, figure 8.2 shows that the regime switch to excess credit supply at price zero already occurs at $s = 0.942$.

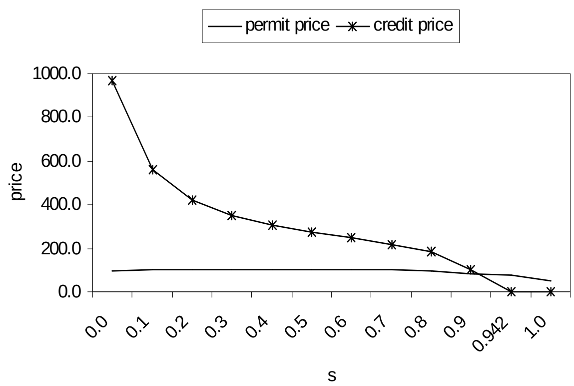

Figure 8.2: *Permit and credit price.*

Under tradable emission permits there is always a total permit supply of 40 and even for $s = 0$ permit demand and supply are equalized at a comparatively modest price ($\sigma = 95.8$). From figure 8.2 it seems that the permit price σ is rather constant; however, this appearance is a scaling effect. The values for σ vary from 95.8 in $s = 0$ to 103.3 in $s = 0.4$ to 48.1 in $s = 1$. The permit price σ develops relatively moderate, also because clean firms are not in a position to sell permits in the early stage of diffusion (this issue will be discussed in section 8.5). The profit advantage of clean firms is considerably lower under the permit regime than it is under credits. It should be noted that compared to permits, the higher profit differential for credits also means that firms will switch faster from the dirty to the clean technology and therefore the evolutionary equilibrium will be realized earlier with credits than with permits.

Let's examine the permit price a bit further. Starting from $s = 0$ (the whole industry is specialized in manufacturing the dirty good), the permit price increases (in a modest way) with s. Relative to the supply of permits, this reflects a situation where the demand for permits (pollution) is high and increasing. In the second stage of diffusion the permit price declines. The reason for the former effect can be found in the production side of the model as shown in figures 8.5 and 8.6 for the laissez faire case. We have seen that total output and emissions tend to increase in the early stage of diffusion. Consequently, the permit price has to rise to depress total output in order to stimulate substitution of clean for dirty output thus keeping the demand for permits low enough to be covered by the available permit supply. The process is reversed in the later diffusion stage. According to figure 8.6, industry emissions under laissez faire are at a maximum at $s \approx 0.4$. The permit price starts to fall from this state on. Apparently, the pressure on the demand for permits becomes less since the corresponding total industry emissions decrease.

The price development of credits is quite different from permits. In figure 8.2 we see that ϕ is consistently decreasing in diffusion s. Moreover, the credit price is extremely high when the penetration of clean type firms is very low. As explained before, as clean production increases, the total allowed emissions go up and simultaneously credit supply (demand) will increase (decrease).

As a next step, the product prices of the dirty and clean product variant are depicted in figure 8.3. Under permits the price of the clean product variant p_c^{per} is decreasing in s. Evidently, this effect results from an increase in price competition on the market for clean products. The price of the dirty good p_d^{per} remains constant as diffusion advances. Because the total amount of dirty output and the fraction of dirty firms both decrease (see figure 8.4), the remaining firms can stick to their old price.

Furthermore, figure 8.3 indicates that the price for clean products under credits p_c^{cre} decreases even faster than p_c^{per}, however, only up to the state $s \approx 0.9$. This is mainly due to clean firms being able to sell credits, which lowers their costs. This goes hand in hand with a rapid declining credit price (as shown in figure 8.2) and therefore lower revenue from selling credits, thus reducing profits more rapidly than for clean products under permits (see figure

8.1). The graph also shows a decreasing price for the dirty product variant under credits (again) up to $s \approx 0.9$. This is the consequence of the sinking credit price, implying lower credit costs for the dirty firms, which are buyers in the credit market.

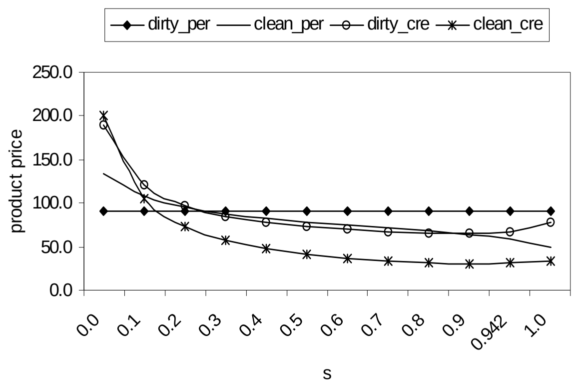

Figure 8.3: *Product prices under permits and credits.*

Lower costs under credits enable lower product prices and an increasing output of dirty firms differently from dirty output under permits as figure 8.4 illustrates. This figure also shows that as the proportion of clean type firms increases, total clean output also grows. This holds under both the permit and credit regime. Under credits, growth is faster because the emission constraint moves up with total output.

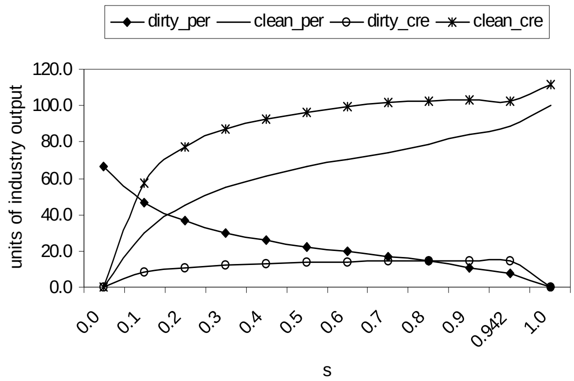

Figure 8.4: *Aggregate clean and dirty output.*

Summation of X_d^k and X_c^k $(k = per, cre)$ yields the total industry supply levels as shown in figure 8.5.

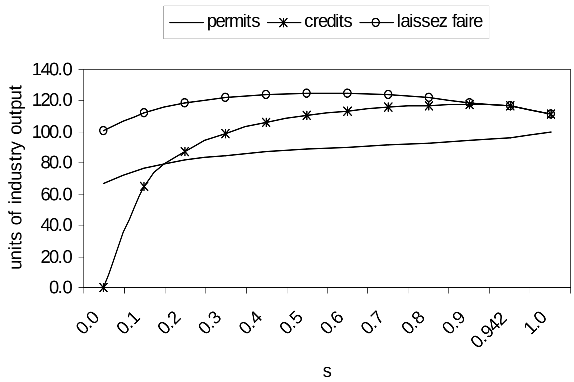

Figure 8.5: *Industry output under permits, credits and laissez faire.*

This example shows that the total volume of industrial output X^{per} increases with diffusion s. This does not imply that industry emissions also increase in the fraction of clean type firms. On the contrary, given the emission ceiling

L in the permit scheme, total industry emissions will never exceed this ceiling due to the simultaneous coordination on the permit and output market (as we outlined before). In this specific example, the total volume of industry emissions E^{per} thus remains at $L = 40$, independent of the diffusion process (see figure 8.6). Regarding total industry supply under credits, figure 8.5 also shows a rise in total output for states $s < 0.9$. But total emissions are not fixed in this case. For convenience, the output levels under laissez faire are also added and will be used for explaining the specific behavior of the permit price that will be dealt with below. In figure 8.6, total emissions are plotted against diffusion s.

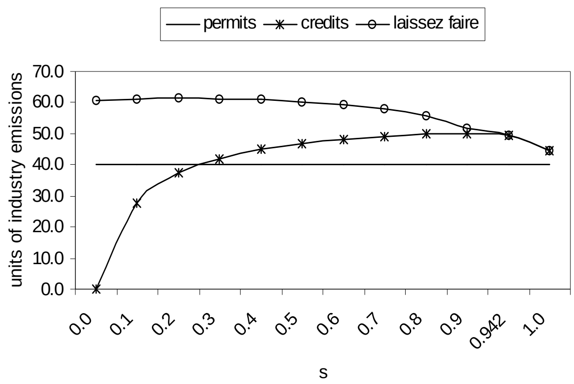

Figure 8.6: *Industry emissions under permits, credits and laissez faire.*

The level of actual and allowed emissions under the credit regime are at a low level for relatively small s. Initially they increase very fast and then start to slow down, but exceed the permit emission level and approach the laissez faire level of emissions. The initial low emission level is due to the high credit price, which chokes output of dirty firms because of high costs. This also implies a low level of allowed emissions. As more and more firms adopt the clean technology, supply of credits increases and the emission constraint slackens. In the end, when diffusion has progressed to a relatively high level, there is an abundance of credits and its price approaches zero (see figure 8.2). From that point on ($s > 0.94$), the credit trading regime actually does not differ any more from laissez faire in terms of output and emissions, as figures 8.5 and 8.6 show.

8.5 A note on permit and credit trade

It has been shown that diffusion under a tradable permit regime is a flexible instrument in the sense that the government controls the total amount of pollution directly by simply setting the overall emission ceiling L invariant of the state of the diffusion process. How the firms meet their individual emission levels is left out of the hands of the control authority. However, so far, the discussion on the permit instrument did not include the trade aspect of permits. Firms were simply endowed with an initial amount of permits, which could be traded among each other in order to regulate their production levels, given the choice of technology. Even without knowing the trade volumes, that is knowing which firm type is a buyer or a seller, the final equilibrium outcome could be determined. Although we mentioned the high production level of the clean firm in the early stage of the diffusion process and therefore its role as a potential buyer of permits, we did not prove this explicitly. Evidently, the individual firm-level production and buyer/seller role are narrowly related to each other. The aim of this section is to determine which types of firms are permit buyers and which types act as sellers under the dynamic specification of the diffusion process.

Following a route where the allocation of permits among the number of firms in the industry proceeds according to a grandfathering rule, each firm is initially endowed with a number of permits $m = L/N$. So, clean and dirty firms receive the same amount of permits. Each permit allows a firm to emit one unit of the pollutant and may be traded among the firms. Now assume that a firm adopts the clean technology. The relevant question is what will be the influence on the decision how much permits to either buy or sell? One could expect the firm-level emissions to decrease when these firms invest in a pollution reducing technology. When this level is below the initial allocation of permits m, it can sell the redundant amount of permits[6]. To determine which firm type is a seller and a buyer, we restrict ourselves to the case of a stable mixture of clean and dirty type firms in the long-run, i.e., a downward sloping profit differential. What we find is that outside the dynamically stable evolutionary equilibrium $\tilde{s}$, the fraction $\bar{s} < \tilde{s}$ are permit buyers.

[6]Remark that this, of course, is only valid without the opportunity of permit banking. When firms are allowed to bank permits they could choose to hold up a certain amount of permits in order to use them for future emissions or future permit sales. However, for the purpose of this section it is not necessary to include a banking opportunity and is therefore omitted.

Proposition 4 *The fraction of firms* $0 < \bar{s} < \tilde{s}$ *are permit buyers.*

Proof. In appendix 8A. ∎

What does proposition 4 say? By definition, the diffusion states $0 < s \leq \tilde{s}$ represent the fraction of firms that have adopted the clean technology. So there exists only a fraction $\bar{s} \in (0, \tilde{s})$ that act as permit buyers and they are all clean firms. We shall give an intuitive sketch behind this result since the formal proof can be found in the appendix. Consider for instance the laissez faire case explored in chapter 6. The numerical illustration in section 6.5 showed that for relatively low values of diffusion s, the optimal firm-level output when the clean technology has been adopted is higher than when the dirty production scheme is adopted. Given the initial allocation of permits m, the individual emission level is also higher than permits owned allow. That is, the initial number of permits cannot cover the individual emission volume of the clean firm when supplying its corresponding optimal level of clean output. In more general terms, proposition 4 states that early innovators (early adopters of the clean technology) in an imperfect competitive product market are permit buyers.

Figure 8.7 provides a graphical illustration. We shall provide a brief technical outline as a guide to figure 8.7.

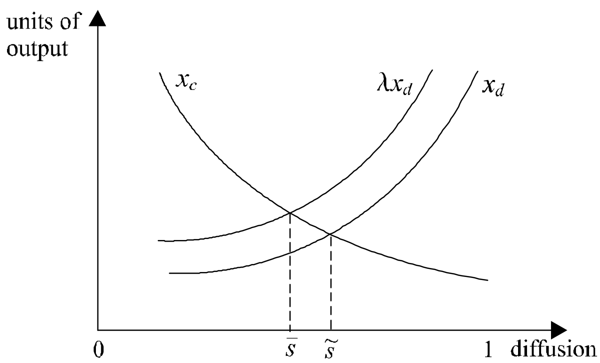

Figure 8.7: *Permit trade and diffusion.*

There is absence of permit trade when the firm-level emissions of the clean and dirty firm are equal, i.e., $e_c = e_d$. As a result, the clean firm is a permit buyer (seller) if and only if $e_c > (<)\ e_d$. Rewriting this in terms of production according to (6.9) and rearranging yields that the clean firm is a buyer (seller) of permits if and only if $x_c > (<) \ \lambda x_d$,where $\lambda = \zeta_d/\zeta_c > 1$. The diffusion point at which there is no permit trade is represented by $\bar{s}$ in figure 8.7. It is the solution to $x_c = \lambda x_d$ (i.e., $e_c = e_d$). As can easily be checked in figure 8.7, $x_c > (<) \ \lambda x_d$ for diffusion states $s < (>) \ \bar{s}$. In other words, when $s < \bar{s}$, the firm-level emissions of the clean firm e_c exceeds the emission level of its dirty competitor e_d. Hence the clean firm acts as the buyer of permits, whereas the dirty firm acts as the permit seller. The reverse holds for diffusion states $s > \bar{s}$. Then the dirty and clean firm are the buyer and seller of permits respectively. Moreover, this implies that in the evolutionary equilibrium $\tilde{s}$, the dirty firm is always the permit buyer because $x_c < \lambda x_d$.

The changing direction of permits traded as diffusion of clean technology proceeds, can be contrasted with the direction of transferred credits in the credit scheme. Here the clean firms are always the seller at any value of diffusion s, because only this type of firm can create credits by emitting less per unit of production than the emission standard allows. The dirty firms are credit buyers because they always emit more per unit of output than the emission standard allows.

8.6 Sensitivity analysis

Now that we have tried to shed light on the behavior of crucial variables, we will turn to a sensitivity analysis of the two policy variants. Like in chapter 6 and 7, we will conduct a sensitivity analysis that incorporates the effects of a changing market structure in terms of a changing cross-price parameter γ. An increase in γ implies that clean and dirty products become closer substitutes. For $\gamma = \beta$, the goods are identical from the consumers' point of view. As before, we will show how the model is affected by a changing market structure in terms of a changing cross-price parameter $\gamma \in [0, \beta]$. We focus on the most essential variables like the composition of dirty and clean industry output, total emissions, product prices, the permit and credit price, and the diffusion process expressed by the profit differential.

The permit price σ and credit price ϕ as given in (8.6) and (8.16) respectively, are plotted in figure 8.8. The credit price is plotted for diffusion states $0 < s \leq 0.98$. Diffusion state $s = 0.98$ is the point calculated given $\gamma = 0$ and is thus the minimum point where ϕ falls to zero. The behavior of the relevant variables for diffusion states $s > 0.98$ coincides with the sensitivity analysis as conducted for the laissez faire case in chapter 6. Consequently, since the credit price affects all other variables, the sensitivity analysis also involves diffusion states $0 < s \leq 0.98$. Regarding the credit price ϕ in the right panel of figure 8.8, we see that $\partial\phi/\partial\gamma < 0$ for $0 < s \leq 0.98$. For $s = 0$ and $s = 0.98$, $\partial\phi/\partial\gamma = 0$. With respect to the permit price as shown in the left panel, $\partial\sigma/\partial\gamma = 0$ in the corner states $s = 0$ and $s = 1$ and $\partial\sigma/\partial\gamma < 0$ for $0 < s < 1$. Taking diffusion as the focal point, the pattern of change under credits remains the same, i.e., for low diffusion states ϕ follows a convex pattern and changes to a concave function as s increases. The permit price (as a function of s) completely transforms from a pure concave function into a convex one in the range $\gamma \in [0, \beta]$.

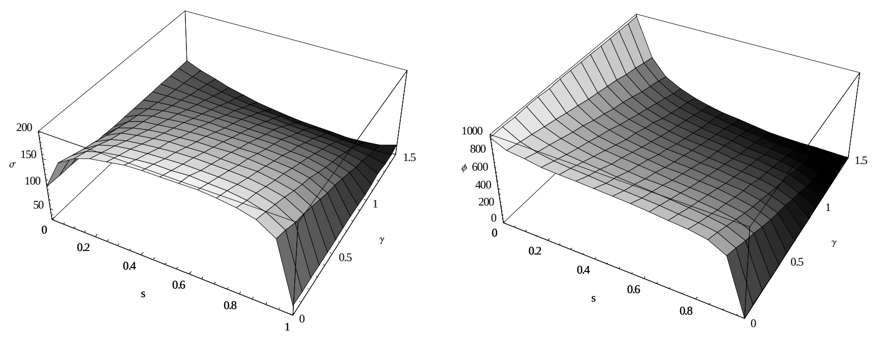

Figure 8.8: *Permit and credit price as function of diffusion and cross-price parameter* γ.

Total emissions under tradable permits are not so interesting since they are equivalent to the fixed supply of permits, i.e., emission ceiling L (see left panel of figure 8.9). A change of γ only affects firm-level outputs, but the simultaneous coordination of the permit and output market result in achieving the constant emission ceiling. It is hard to see, but under credits as depicted in the right panel of figure 8.9, total emissions decrease as the substitutability between the dirty and clean product increases: $\partial E^{cre}/\partial\gamma < 0$. As we see, emissions are quite robust to changes in the market structure in terms of a change in the degree of product differentiation.

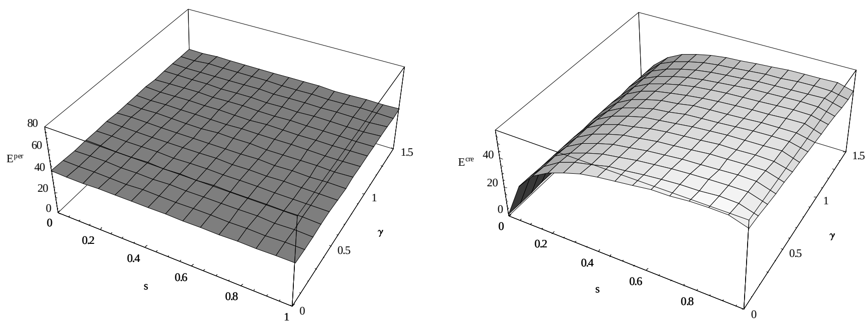

Figure 8.9: *Industry emissions as function of* s *and cross-price parameter* γ*.*

The result $\partial E^{cre}/\partial\gamma < 0$ can be derived from the fact that both X_d^{cre} and X_c^{cre} are also decreasing in γ. Figure 8.10 shows the composition of the dirty and clean industry output levels as a function of diffusion s and γ. The upper panel refers to the permit regime, the lower panel to the credit policy. First, the permit case. We see that for all $\gamma \in [0, \beta]$ aggregate dirty output X_d^{per} and aggregate clean output X_c^{per} is decreasing, respectively increasing in s. When the goods are independent ($\gamma = 0$), X_d^{per} is first convex for low s and then gradually becomes concave. As γ increases, X_d^{per} becomes strictly decreasing and purely convex in s. The reverse happens to X_c^{per}: when $\gamma = 0$, X_c^{per} is concave in the first stage of diffusion and then gets convex. As γ rises, X_c^{per} gets concave and increasing in s. Compared to the situation where $\gamma = 0$, the fall in X_d^{per} is less in $\gamma = 1.5$ for low s. As the demand for the dirty good gets more inelastic to the price of the clean good, and eventually become close substitutes, consumers will have a higher preference for the dirty good (relative to the clean good) when the clean technology has not penetrated the industry to a large extent (s is low). This effect also comes forward in the upper panel of figure 8.10. In the upper-left and upper-right panel respectively, we see that for $\gamma = 1.5$ and s close to zero that X_d^{per} (X_c^{per}) do not decrease (increase) as much than when $\gamma = 0$. Under credits (depicted in the lower panel), we see that X_d^{cre} and $X_c^{cre}$are more or less similar. They only differ in their absolute levels, i.e., $X_d^{cre} < X_c^{cre}$ for all $s \in [0, 1]$ and all $\gamma \in [0, \beta]$.

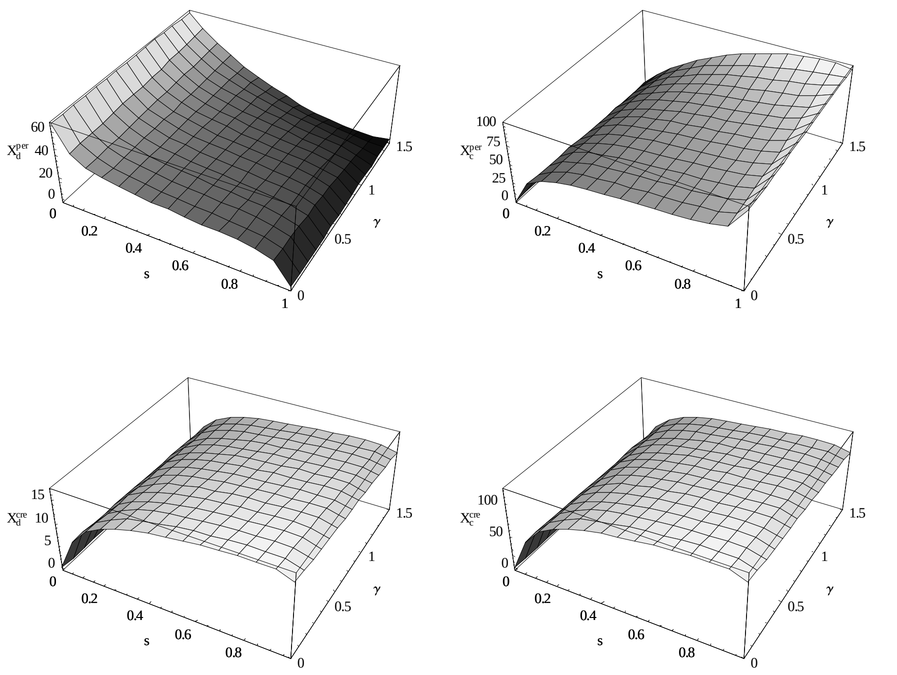

Figure 8.10: *Aggregate dirty and clean output as function of diffusion and cross-price parameter* γ*.*

Comparative static results with respect to the output prices under permits and credits are given in figure 8.11. Let's first consider the corner states $s = 0$ and $s = 1$ again. In these diffusion states $\partial p_j^{cre}/\partial\gamma = 0$ $(j = d, c)$. Under the tradable permit policy, we find in $s = 0$ that $\partial p_d^{per}/\partial\gamma = 0$ and $\partial p_c^{per}/\partial\gamma < 0$. The reverse holds when the industry is completely specialized in the production of the clean good $(s = 1)$. Then $\partial p_d^{per}/\partial\gamma < 0$ and $\partial p_c^{per}/\partial\gamma = 0$. In general, for states $0 < s < 1$, a change in the market structure reflected by the degree to which the products are substitutes, appears to have a minor effect on the prices under the permit regime. In the figure this is reflected by rather flat surfaces in the upper panel for a large range of both s and γ. The cross-price parameter γ seems to play a somewhat bigger role under the credit policy. The dirty output price decreases when product substitutability increases: $\partial p_d^{cre}/\partial\gamma < 0$. On the other hand, the clean output prices are slightly increasing in γ for $s \in (0, 1)$, i.e., $\partial p_c^{cre}/\partial\gamma > 0$.

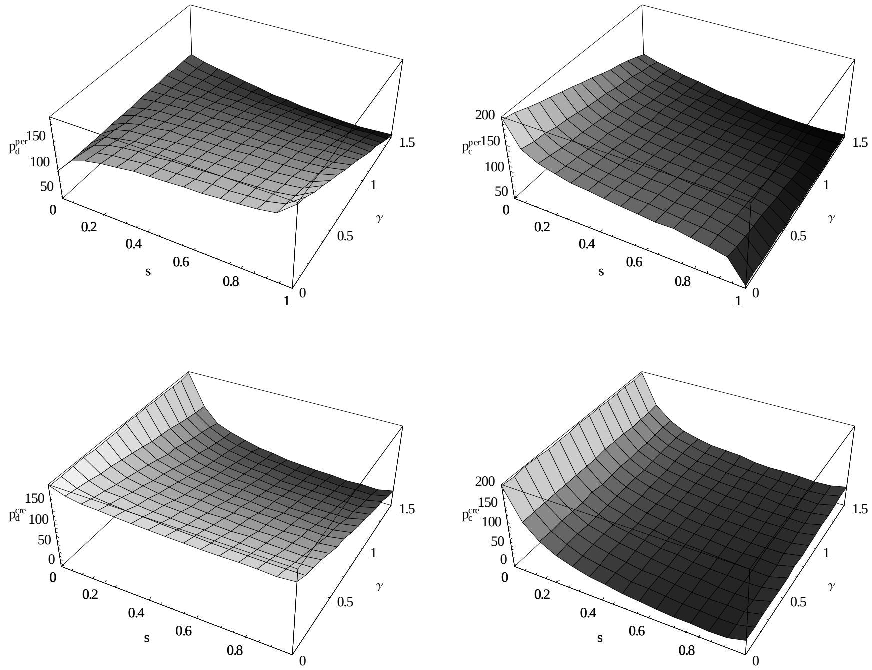

Figure 8.11: *Product prices as function of diffusion and cross-price parameter* γ.

Finally, let's take a look at how the profit differential $\Delta\pi$ is affected by the degree of product substitutability. This is presented in figure 8.12. We see that a change in γ does not have significant impact on the profit differential under credits. Under permits, the influence of γ on $\Delta\pi$ seems to play a significant role only in the neighborhood of the corner states. When γ is rather low, the profit differential is downward sloping in s, following a convex pattern in the first stage of diffusion and a concave pattern in the second stage. The differential $\Delta\pi$ is very close to zero for all $s \in [0, 1]$ when γ approaches the level of $\beta = 1.5$.

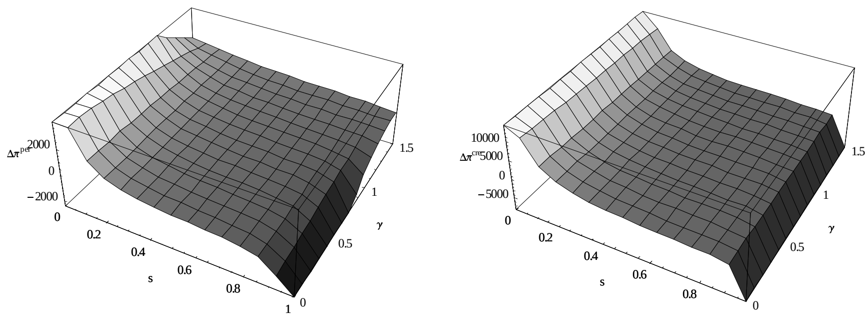

Figure 8.12: *Profit differential as function of diffusion and cross-price parameter γ.*

To recapitulate the most relevant findings, in general, a decreasing degree of product heterogeneity does not have significant qualitative consequences to the model. However, as products become closer substitutes, the permit price changes from concave to convex in diffusion s. That is, in case of perfect product substitutability ($\beta = \gamma$) and diffusion s very high, the permit price starts to increase with s.

So far, we have tried to shed some light on the permit and credit policy and provided a numerical illustration in order to gain some insight into the rationale and intuition behind these two policies. In the next section, we will put our emphasis on the diffusion process again and try to derive the evolutionary equilibria.

8.7 Concluding remarks

This chapter explored the environmental policy instruments tradable emission permits and tradable emission credits. The fundamental difference between the two instruments is that under a system of tradable permits the *overall* industry emission target is fixed and independent of industry output. Under a tradable credit system the emission target is tied to industry output. The target for the industry is not to exceed a specified quantity of emissions per unit of output. A tradable credit scheme is basically direct regulation by emission standards with credit trade, creating the flexibility for individual firms to choose a higher or lower emission/output ratio than the emission standard.

Under a tradable permit system, a more stringent environmental target by a lowering of the emission ceiling results in a higher equilibrium degree of clean technology diffusion in the long-run, provided the clean firm faces a net absolute advantage which is at least as high as the net absolute advantage of the dirty firm. This holds in a Cournot product market where the goods are either imperfect or perfect substitutes. So, a varying degree of product differentiation does not impose any constraints in supporting the adoption and diffusion of clean technology by introducing a more stringent environmental policy. Within a tradable credit system, the pursuit of a stricter environmental policy by tightening the emission standard also affects diffusion of clean technology positively. This result is invariant to the degree of product heterogeneity.

In comparing the economic variables under the two policy regimes, the point of departure has been that both yield the same long-run equilibrium degree of diffusion. Then the emissions per unit of production under permits and credits are equal. In the diffusion equilibrium, the prices of both the clean and dirty product variant are higher under permits than they are under credits. The costs of emissions per unit of production are higher under permits since under credits only *excess* emissions involve credit costs and under permits *all* emissions bear permit costs. The credit instrument is therefore more attractive than permits from a consumer's point of view. Lower product prices under credits also involve a higher volume of total output, making the level of emissions also higher compared to a permit scheme. This makes the price for emissions in the equilibrium higher under credits relative to permits.

A striking feature are the big differences between the permit and credit market in terms of demand and supply conditions, market prices and trade flows. The credit price seems much more sensitive to changes in diffusion than the permit price. The initiation of the diffusion process implies an extremely high credit price, which falls sharply as diffusion advances; the permit price first rises in the early stage of diffusion and then starts to decrease again, but remains below the price of credits. The explanation is mainly due to supply conditions. Whereas under permits there is a constant supply of permits over the whole diffusion period, under a credit scheme there is hardly any supply of credits in the initial stage of diffusion. This low supply of credits is followed by an increasing quantity of credits as diffusion of clean technology progresses.

With respect to the tradable permit regime, we proved that as diffusion evolves from the initial state where the whole industry employs the dirty technology, the firm who adopts the clean technology is a permit buyer. It has been shown that this specific buyer/seller role continues until a certain diffusion state is reached, which is lower than the evolutionary stable diffusion equilibrium. As a result, the roles have changed in the diffusion equilibrium where the clean firm is a seller of permits and the dirty firm a buyer. This suggests that developing clean production when the market for products is imperfectly competitive not necessarily means that firm-level emissions decline as a result from the adoption of clean technology and hence the opportunity to sell a permit surplus. Rather the reverse situation occurs; investment in clean technology by the innovating firm implies permit buying in the early stage of the diffusion process. However, with credit trade clean firms are always the sellers of credits and dirty firms the buyers.

Given the calibration of the permit and credit model, emissions are higher in the evolutionary equilibrium under a tradable credit regime than under permits. Taking the whole diffusion period into consideration one sees that, compared to permits, emissions under credits are lower in the early stage of diffusion and higher in the later stage. If we consider the whole diffusion process, credits seem to be better for consumers than permits, in particular due to the lower prices for clean products. What on the other hand comes out quite clearly is that a credit policy causes a much bigger shock to the industry than a permit scheme. Output of non-adopters of clean technology is almost wiped out in the early stage of diffusion due to credit shortage. The positive side is that through this process of creative destruction (Schumpeter, 1942), the diffusion of clean technology speeds up, as can be concluded from the much bigger profit differentials for credits than for permits during transition.

The finding that a tradable credit scheme causes the process of economic adjustment to be more painful than it would have been with a system of tradable emission permits, is in conflict with common wisdom among Dutch policy makers and lobbyists from industry. They argue that emission standards in combination with tradable credits are less hard for the industry than a cap and trade programme. For that reason preparations are in progress for a scheme of tradable NO_x emission credits for energy intensive industries to be introduced in the second half of 2004. For the same reason, the Committee Vogtländer (2001) proposed to organize CO_2 emission trading for the energy intensive industries in the Netherlands in the form of credit trading and not as a scheme of tradable emission permits as the European Commission in a recent proposal for a directive is aiming for. Our analysis of diffusion of clean technology has shown that the economic impacts of the two distinct schemes differ extremely. It is therefore hard to imagine that they can peacefully coexist within the European Union.

8.8 Appendix 8A

Proof of proposition 2

Proof. The denominator of (8.17) is positive due the quadratic term. Shifting our attention to the numerator. By doing some rewriting, the term

$$\beta(N+1)(\zeta_c^2+\zeta_d^2)-2(\beta+\gamma N)\zeta_c\zeta_d>0 \Longleftrightarrow \beta/\gamma>\frac{2N\zeta_d\zeta_c}{(N+1)(\zeta_d^2+\zeta_c^2)-2\zeta_d\zeta_c}.$$

By definition, $\beta/\gamma>1$. If we can prove that the right-hand-side term

$$\frac{2N\zeta_d\zeta_c}{(N+1)(\zeta_d^2+\zeta_c^2)-2\zeta_d\zeta_c}<1,$$

the inequality would hold. This term can be written as:

$$\begin{aligned}
2N\zeta_d\zeta_c &< (N+1)(\zeta_d^2+\zeta_c^2)-2\zeta_d\zeta_c\\
2N\zeta_d\zeta_c+2\zeta_d\zeta_c &< (N+1)(\zeta_d^2+\zeta_c^2)\\
2\zeta_d\zeta_c(N+1) &< (N+1)(\zeta_d^2+\zeta_c^2)\\
2\zeta_d\zeta_c &< (\zeta_d^2+\zeta_c^2).
\end{aligned}$$

This holds for all positive values, hence $\beta(N+1)(\zeta_c^2+\zeta_d^2)-2(\beta+\gamma N)\zeta_c\zeta_d>0$. Now what is left is the term $\zeta_c\theta_d-\zeta_d\theta_c$ in the numerator of (8.17). Since we have shown that all terms are positive, $\partial\tilde{s}^{per}/\partial L \gtreqless 0 \Longleftrightarrow \zeta_c\theta_d-\zeta_d\theta_c$, which holds if and only if $\zeta_d/\zeta_c \lesseqgtr \theta_d/\theta_c$. ■

Proof of proposition 4

Proof. Given the overall emission target L, each firm initially receives a number of permits equal to $m=L/N$. Given the state s, the individual emission level of the clean firm is $e_c=\zeta_c x_c$. When $e_c>(<)\ m$, the clean firm pollutes more (less) than can be covered by the amount of permits m and therefore has to buy (sell) an additional number of permits equal to $e_c-m>(<)\ 0$. We have to determine when this holds. The overall emission goal (8.5) reads:

$$L=\zeta_d X_d+\zeta_c X_c.$$

Dividing L by the number of firms N, the initial amount of permits m equals:

$$\begin{aligned}
m &= \frac{\zeta_d X_d+\zeta_c X_c}{N}\\
&= \frac{\zeta_d(1-s)Nx_d+\zeta_c sNx_c}{N}\\
&= \zeta_d(1-s)x_d+\zeta_c s x_c.
\end{aligned}$$

We know that when $e_c > m$, the clean firm buys permits. Writing out, this inequality becomes:

$$\begin{aligned}\zeta_c x_c &> \zeta_d(1-s)x_d + \zeta_c s x_c \\ \zeta_c(1-s)x_c &> \zeta_d(1-s)x_d \\ \zeta_c x_c &> \zeta_d x_d \\ e_c &> e_d.\end{aligned}$$

Hence the dirty firm sells permits to the clean firm. Obviously, no permit trade occurs when $e_c = e_d$, i.e.,

$$\begin{aligned}\zeta_c x_c &= \zeta_d x_d \\ x_c &= \lambda x_d,\end{aligned}$$

where $\lambda = \zeta_d/\zeta_c > 1$. Solving $x_c = \lambda x_d$ for s gives the state of diffusion $\bar{s}$ at which there is absence of permit trade. On the other hand, the evolutionary equilibrium $\tilde{s}$ is the solution of the equal profit condition $\pi_d = \pi_c$, reflecting the state at which there is no incentive for switching technologies. More precisely, based on equation (6.17) and given fixed costs are zero, the equal profit condition reduces to the solution where the quantities supplied by the dirty and clean firm type are equal:

$$\begin{aligned}\pi_d &= \pi_c \\ \beta x_d^2 &= \beta x_c^2 \\ x_d &= x_c.\end{aligned}$$

Because $\lambda > 1$, dirty production increases for all $s \in [0,1]$ and because $dx_d/ds > 0$ and $dx_c/ds < 0$, the intersection point $\bar{s}$ where $x_c = \lambda x_d$ (representing no permit trade) lies to the left of the evolutionary equilibrium $\tilde{s}$ where $x_c = x_d$. Therefore, the fraction of firms that are permit buyers is on the interval $0 < \bar{s} < \tilde{s}$. ■